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Cybersickness Onset with Reflexive Head Movements During Land and Shipboard Head-Mounted Display Flight Simulation

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14. ABSTRACT

Military communities have long recognized the value of using flight simulations for enhancement of mission performance. Although flight simulators depicting virtual images of mission profiles are known to improve situational awareness, pilots using head-mounted display virtual reality (HMD/VR) environments often report increased signs and symptoms associated with simulator sickness. With shipboard deployment of HMD/VR training devices, disparity between VR visual flight conditions and ship induced vestibular accelerations may generate changes in reflexive head movement, and thereby influence risk of simulator sickness. In this study, nine subjects flew a head-mounted display HMD/VR flight simulation during land based and shipboard conditions. Reflexive head positioning and simulator sickness questionnaires (SSQ) were used to evaluate differences between the two conditions. Results indicate that both land and shipboard HMD/VR flight simulations produced optokinetic cervical reflex (OKCR) responses ($p < 0.001$) in both coronal and sagittal planes; however between land and sea conditions, these OKCR variations were not statistically significant. In contrast, land and sea OKCR head yaw did show a significant increase during shipboard trials. With respect to simulator sickness, SSQ scores were significantly elevated after exposure to both land and sea HMD/VR conditions; however SSQ differences (between land and sea conditions) did not reach a significant level. In summary, non-motion (land) HMD/VR flight simulations provoke significant coronal and sagittal OKCR responses that do not change when low sea state shipboard motion is introduced; however, low sea-state shipboard motion did appear to trigger significant increases in OKCR head yaw. With regard to predicting the early onset of cybersickness, correlations between coronal OKCR and SSQ data suggest the possibility of an inverse trend between reported simulator sickness and head movement.

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The study protocol was approved by the Naval Aerospace Medical Research Laboratory Institutional Review Board in compliance with all applicable Federal regulations governing the protection of human subjects.

EXECUTIVE SUMMARY

Military communities have long recognized the value of using flight simulations for enhancement of mission performance. Although flight simulators depicting virtual images of mission profiles are known to improve situational awareness, pilots using head-mounted display virtual reality (HMD/VR) environments often report increased signs and symptoms associated with simulator sickness. With shipboard deployment of HMD/VR training devices, disparity between VR visual flight conditions and ship induced vestibular accelerations may generate changes in reflexive head movement, and thereby influence risk of simulator sickness. In this study, nine subjects flew a head-mounted display HMD/VR flight simulation during land based and shipboard conditions. Reflexive head positioning and simulator sickness questionnaires (SSQ) were used to evaluate differences between the two conditions. Results indicate that both land and shipboard HMD/VR flight simulations produced optokinetic cervical reflex (OKCR) responses ($p < 0.001$) in both coronal and sagittal planes; however between land and sea conditions, these OKCR variations were not statistically significant. In contrast, land and sea OKCR head yaw did show a significant increase during shipboard trials. With respect to simulator sickness, SSQ scores were significantly elevated after exposure to both land and sea HMD/VR conditions; however SSQ differences (between land and sea conditions) did not reach a significant level. In summary, non-motion (land) HMD/VR flight simulations provoke significant coronal and sagittal OKCR responses that do not change when low sea state shipboard motion is introduced; however, low sea-state shipboard motion did appear to trigger significant increases in OKCR head yaw. With regard to predicting the early onset of cybersickness, correlations between coronal OKCR and SSQ data suggest the possibility of an inverse trend between reported simulator sickness and head movement.

INTRODUCTION

The purpose of this study was to determine if shipboard deployment of head-mounted display virtual reality (HMD/VR) flight simulators will increase risk of simulator sickness and thereby negatively impact aircrew performance. At sea, uncontrollable variables, such as wind and wave action, are likely to generate ship motion incongruent with aircraft movements displayed on an embarked flight simulator; consequently, flight crews using a shipboard flight simulator may be at increased risk of simulator sickness due to sensory discord between vestibular, proprioceptor, and visual systems. Previous research has demonstrated that use of a fixed monitor flight simulator, during low sea state conditions, has a negligible impact on reported simulator sickness; however, during this previous experiment, significant decrements in dynamic visual acuity were measured following 60 minutes of exposure to flight simulation accompanied with mild ship motion (1).

Background

Currently, many of the world's military organizations are aggressively developing advanced technologies involving HMD/VR environments. The impetus behind this research is to enhance training and operational performance, while simultaneously reducing associated costs and hardware "footprint" requirements. In conjunction with these efforts, the United States Military has sponsored multiple projects aimed at integrating VR technology with state-of-the-art HMDs (2, 3). Results from this research have greatly improved HMD quality and at the same time, enhanced VR software capability in terms of scene fidelity and real world (satellite) image transformation. Although, recent technological successes have shown promise for expanding the use of HMD/VR simulations; the obstacle of HMD/VR simulator sickness persists as a prominent and debilitating problem.

For many years, simulator sickness has been recognized as a cognitive and physiological threat, capable of negatively impacting pilot performance for up to six hours after exposure (4, 5). Incidences of simulator sickness have reportedly been as high as 45% with fixed monitor or dome-based systems, and in some cases greater than 60% during exposure to HMD/VR simulations (6). As further evidence of this emerging problem, VR devices are now associated with a new classification of sensory induced illnesses described as cyberpathologies. The most serious and prevalent among these maladies is a sensory-spatial disorder referred to as cybersickness (7).

An additional concern for VR training programs are reports suggesting a significant risk of cybersickness exists for relatively short periods of exposure. Recent studies examining onset and frequency of VR illnesses indicate HMD sensory stimuli may produce cybersickness in a matter of minutes, with documented morbidity rates of greater than 75% following 45 minutes of exposure (8).

Although the effects and symptoms of cybersickness have just recently fallen under medical scrutiny, closely related illnesses such as motion or simulator sickness suggest a common etiology among these ailments. Specifically, sensory-spatial conflict resulting

from unexpected environmental changes is typically identified as a causal factor of most sensory induced illnesses. Since even minimal exposure to an inadequately designed HMD/VR system can pose considerable risk to aircrew members, the aim of this study was to quantify both frequency and magnitude of HMD/VR cybersickness in an operational (shipboard) setting.

METHOD

The study protocol was approved in advance by the Naval Aerospace Medical Research Laboratory Institutional Review Board. Each subject provided written informed consent before participating. To evaluate the impact of using HMD/VR systems aboard deployed vessels, nine active duty U.S. Navy volunteers were recruited to participate in land and shipboard based HMD flight simulations. For this within subjects' experimental design, the main independent variable was defined as presence, or absence, of non-synchronous external (ship) motion during HMD/VR flight simulation. Dependent variables chosen for evaluation were the opto-kinetic cervical reflex (OKCR) and comparison of pre and post simulator sickness questionnaires (SSQ) (9, 10).

Volunteer subjects were all physically qualified for duty with the U.S. armed forces and ranged in age from 26 to 45 ($\overline{X}$ = 36 ± 6 yrs). Participants were advised they would be required to complete three HMD/VR flight simulations, one of which would be performed aboard a small underway Navy vessel. In addition to one HMD/VR ship trial, subjects were told they would also need to complete a shipboard control trial (no HMD/VR visual stimulus), during which time they would perform an audio counting task while blindfolded.

For HMD/VR ship and shore conditions, subjects used a head tracked flight simulation to fly a predetermined 60 min course. The simulation incorporated a PROTEC-High RES ® HMD with dual rectangular liquid crystal displays. The combined HMD/VR simulator system provided two rectangular 640 x 480 color images, with 100% overlap and a 42º diagonal field of view (34º horizontal x 26º vertical). To provide visual images consistent with virtual reality environments, a Polhemus FASTRAC ® head tracking system was used to synchronize the "outside" view with changes in subjects' head position.

The simulated flight task required that pilot subjects use stick and throttle controls to navigate through digitized satellite imagery (10 meter resolution) of the Navy's primary flight training area surrounding Pensacola, Florida. A yellow "follow-me" line was digitally imbedded onto the VR imagery to aid with navigation around turns (20 right and 14 left) that made up the assigned route. Display of flight instruments was accomplished by digitally overlaying a virtual (visible when looking forward) heads-up display (HUD) onto the HMD. While transiting through the course, subjects were instructed to maintain their simulated aircraft at an altitude of 5000 ft above mean sea level, with 500 knots of indicated airspeed.

Each subject's first flight simulation was conducted on land, inside a darkened trailer; this trial was used exclusively for familiarization and training with the HMD/VR system. Performance tasks for the second and third flight simulations were identical to the first, with the exception of the third trial being conducted onboard a small U.S. Naval vessel, formally classified as a "YP" or yard patrol craft (108 ft length, 22 ft 9 in beam, and 8 ft draft, Figure 1). Due to scheduling and logistical limitations, the order of trials for sea and land conditions was not randomized. During the HMD/VR sea trials, subjects went aboard the vessel for approximately 1.5 hours, during which time they flew a flight simulation below deck in a darkened, forward, centerline compartment. The shipboard based flight simulations were performed with the vessel underway, in protected coastal waters of Pensacola Bay, Florida. In addition to having the HMD/VR flight simulation equipment onboard the vessel, accelerometers were used to measure and record the ship's linear and rotational accelerations in x, y, and z axis. During HMD/VR and control condition (blindfolded) sea trials, the ship departed Naval Air Station Pensacola's dock facility with subject, experimenters, and crew onboard. After transiting for approximately 15 min to the central portion of Pensacola Bay, the YP craft began following a clockwise octagonal course that required approximately 30 minutes for completion; two circuits of the octagonal course were completed to allow subjects adequate time for completion of the 60 min flight simulation. While navigating the octagonal course, the helmsman maintained a target speed of six knots and used full right rudder deviation, for 15 seconds, to make the required 45º heading change for each new course leg.

YP 676 Class
Diesel powered, twin screw

Length:	108'
Beam:	22' 9"
Draft:	8'
Max Speed:	12 kts
Cruising Radius:	1800 nm

Figure 1: U.S. Navy Yard Patrol Boat used as the ship stimulus.

During HMD/VR sea trials, simultaneous sampling of flight simulation parameters and head position was accomplished every ½ second (2 Hz.) via an interface with the HMD/VR desktop personal computer system. For both HMD/VR and blindfolded sea trials, underway ship accelerations were digitally sampled and recorded at one second intervals (1 Hz.) with a notebook PC computer.

During pre and post HMD/VR flight simulations (land and sea), and pre and post shipboard blindfold trials, subjects completed SSQ surveys to determine whether or not they were experiencing symptoms associated with motion or simulator sickness (10).

RESULTS

Independent variables. Sea states for all nine shipboard trials consisted of a light chop with waves less than two feet. During sea trials, the mean time necessary to navigate twice around the octagonal course was 54.0 $\pm$ 3.4 minutes, with course legs averaging 3.6 $\pm$ 0.1 minutes, and pre/post course transit times lasting for 17.9 $\pm$ 6.8 minutes. A one-way analysis of variance (ANOVA) indicated sea trial course completion and individual leg times did not differ significantly among subjects. While navigating the straight portion of each octagonal leg, average ship roll and pitch was 0.63º $\pm$ 0.58 and -0.34º $\pm$ 0.12, respectively. The time necessary for turning onto each new course leg ranged between 19.7 and 26.2 seconds ($\overline{X}$ = 24.0 $\pm$ 2.0 sec). During these 15 scheduled course turns, subjects were exposed to leftward roll angles that reached an average peak of 1.22º $\pm$ 0.07 with a roll rate of – 0.51º $\pm$ .05 per second; peek acceleration forces generated by these turns equated to 0.003 $\pm$ 0.003 (+Gx), 0.006 $\pm$ 0.001 (–Gy), and 0.98 $\pm$ 0.003 (+Gz).

Subjects completed their shipboard HMD/VR flights (conducted during transit of the octagonal course) in approximately 59.4 $\pm$ 2.0 minutes. The land based fixed flight simulations required an average completion time of 60.5 $\pm$ 1.5 minutes; which did not differ significantly from the shipboard condition.

Dependent variables. During both land and shipboard HMD/VR flight simulations, changes in simulated aircraft attitude (roll, pitch, and yaw) were divided into five degree increments, or bins; head tracking data samples, taken at a rate of 2 per second, were then averaged for each corresponding attitude bin. An ANOVA comparing simulated aircraft attitude and changing head position, indicated that during both land and sea conditions, a significant opto-kinetic cervical reflex (OKCR) occurred for all nine subjects. For both conditions, HMD/VR simulations provoked a predictable OKCR coronal head tilt (p < 0.001) whenever aircraft angle of bank (AOB) increased (Fig. 2). With 90º of simulated AOB, land based and shipboard coronal OKCR peaked at a respective 10.0º $\pm$ 4.4 and 9.8 + 3.3 degrees. The most linear portion of the coronal OKCR response (previously reported as occurring within zero to 35 degrees AOB; 9), indicated a slope value of -0.14 $\pm$ 0.06 for land and -0.13 $\pm$ 0.06 for shipboard conditions. Although changes in perceived AOB produced significant coronal OKCR, an evaluation of this response using student's t-test and regression analysis indicated no significant difference between the land and shipboard conditions.

Similarly, changes in AOB produced significant sagittal OKCR responses (ANOVA, p < 0.001), that did not differ significantly between conditions (Fig. 3). During the HMD/VR flight simulations, ranges of OKCR head pitch were –3.3 ± 3.8 to 6.8 ± 5.9 on land, and –4.0º ± 5.6 to 7.6º ± 9.7 at sea (Fig. 3).

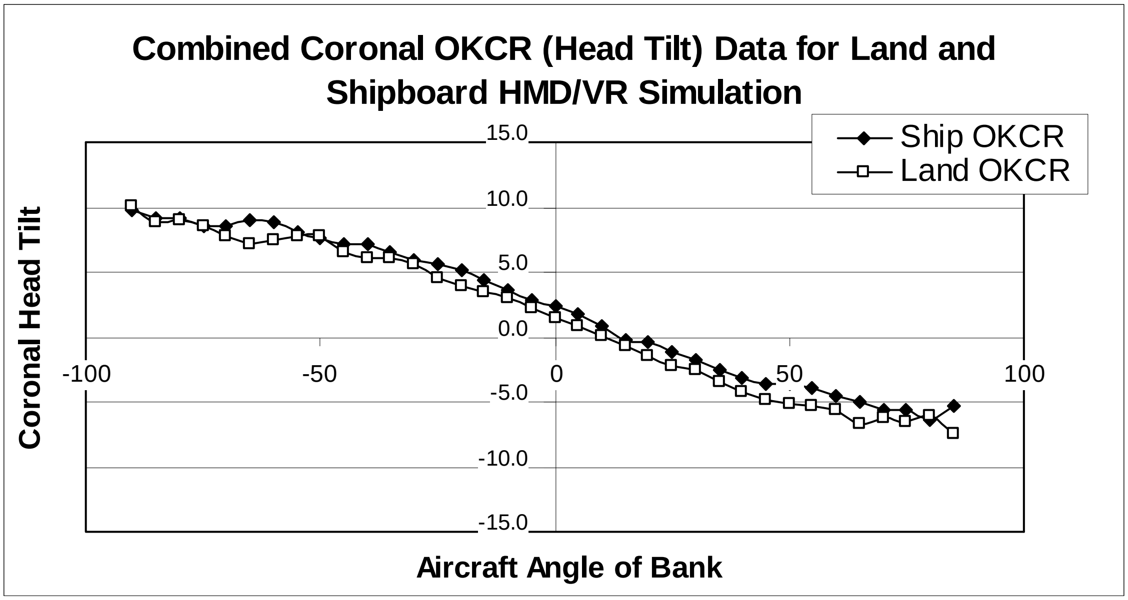

Figure 2: Coronal OKCR (head tilt) vs. angle of bank, during both land based and shipboard HMD/VR flight simulation.

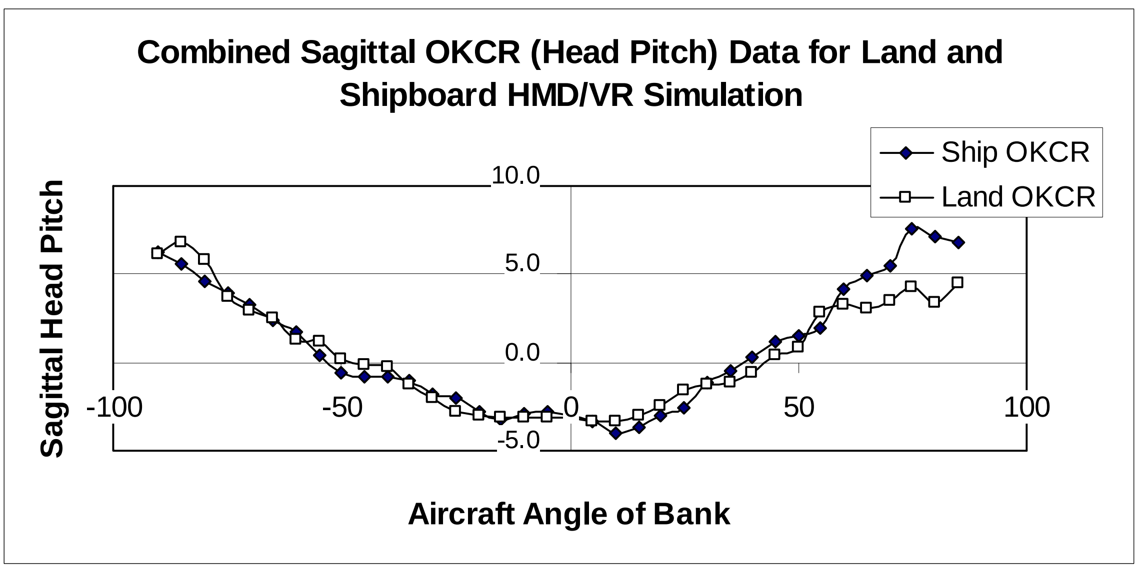

Figure 3: Vertical OKCR (head pitch) vs. angle of bank, during both land based and shipboard HMD/VR flight simulation.

Similar to OKCR evaluations of head tilt and pitch, ANOVA indicated that yawing head movements (turning in a plane horizontal to the deck or floor) were significantly related to HMD/VR flight simulation bank angles; averaged head yaw movements reached a peak of 12.4 $\pm$ 5.4 degrees for shipboard conditions and 7.4 $\pm$ 4.7 for land (Fig

4). However, in contrast to coronal and vertical OKCR, the land and sea conditions presented significantly different results with respect to levels of induced head yaw. A Student *t*-test comparing each subjects regression line (slope or r^2) for head yaw and AOB, indicated OKCR head yaw was significantly greater ($p = 0.04$) during the shipboard condition; averaged (n = 9) slope values were 0.16 $\pm$ 0.09 for sea, and 0.13 $\pm$ 0.09 for land.

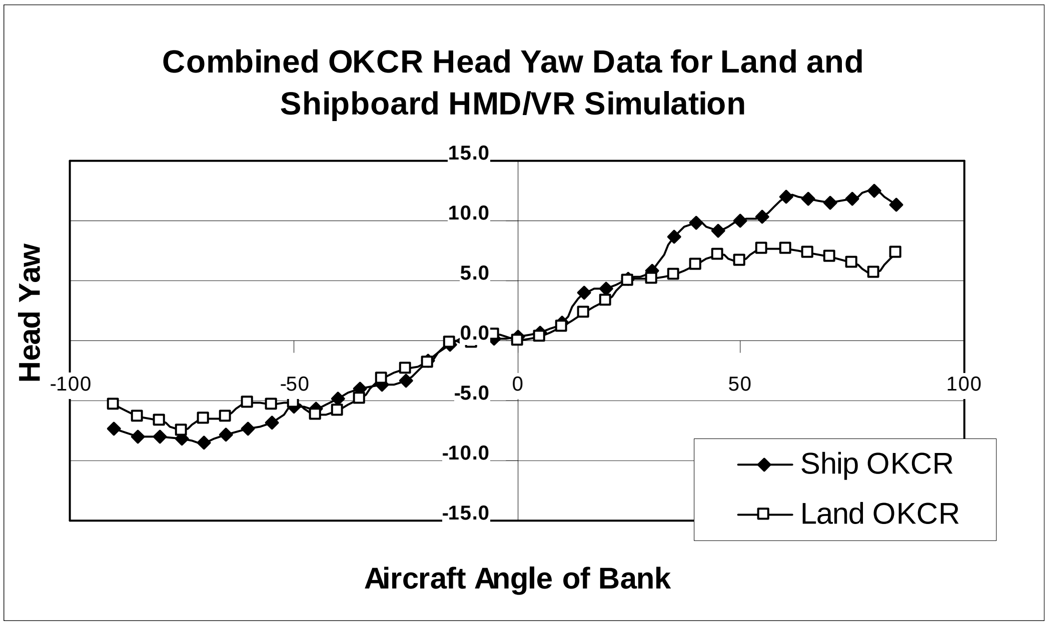

Figure 4: Horizontal OKCR (head yaw) vs. angle of bank, during both land based and shipboard HMD/VR flight simulation.

Simulator sickness questionnaires (SSQ) administered during land HMD/VR, shipboard HMD/VR, and shipboard blindfolded (control) conditions were scored in accordance with guidelines established by Kennedy (10). Pre simulation questionnaires indicated an absence of discomfort, in contrast to the post SSQ's which revealed all subjects experienced simulator sickness symptoms ranging from very mild to severe (Fig. 5). When compared to pretrial SSQ scores (which were essentially zero for all subjects), post SSQ scores indicated all three of the experimental conditions (land HMD/VR, shipboard HMD/VR, and shipboard blindfolded) caused significant increases in reported simulator sickness symptoms. Post trial SSQ scores for land HMD/VR ranged from 3.74 to 48.62 with an average rating of 26.6 $\pm$ 15. Shipboard HMD/VR conditions induced a greater SSQ range that extended from 3.74 to 78.5, with a slightly smaller average of 23.7 $\pm$ 28. The shipboard blindfold condition produced a relatively low post SSQ average of 5.0 $\pm$ 6, with a range of 0 to 14.96. A modified Bonferonni test indicated SSQ scores taken during the shipboard blindfolded condition were significantly ($p < .03$) lower then either the land or shipboard HMD/VR trials. Although differences between land and shipboard HMD/VR conditions did not reach a significant level, the large

variance encountered with the relatively small number of subjects suggest a larger subject pool may be needed for an accurate comparison. Also adding to potential desensitization of SSQ scores was the fact that prior to collecting data for sea HMD/VR trials, all subjects received an initial HMD/VR land based training session and one land based HMD/VR experimental trial that may have provided some opportunity for sensory adaptation.

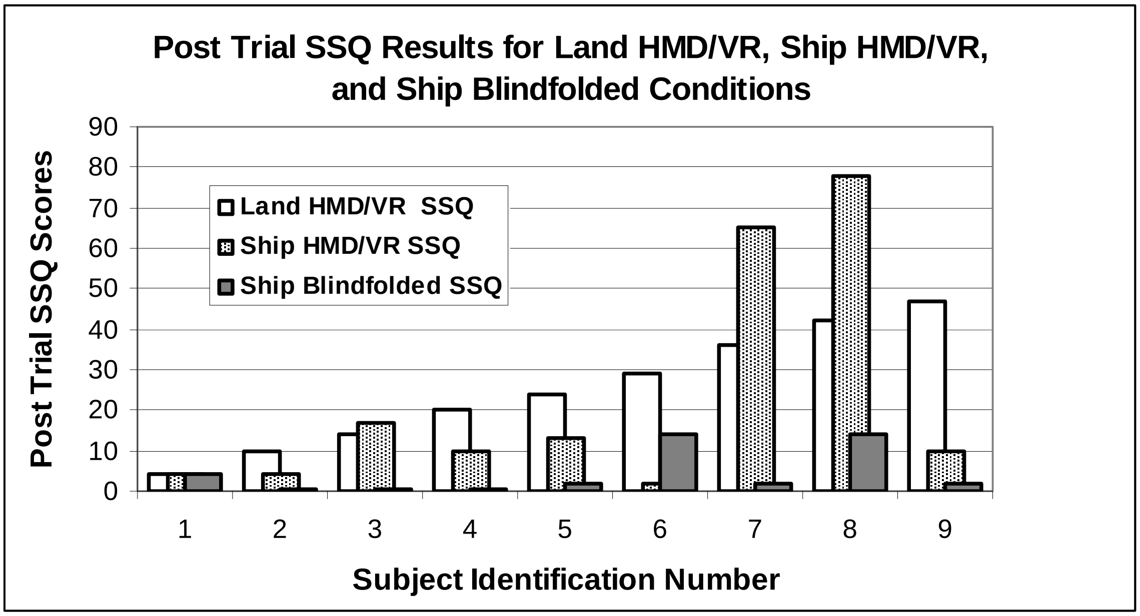

Figure 5: Comparison of each subjects' post SSQ scores during all three conditions (land HMD/VR, ship HMD/VR, and ship blindfolded.

To evaluate the possibility of using reflexive head tilt variations as an indicator of early onset cybersickness, individual SSQ differences between land and sea conditions were calculated and then compared with coronal OKCR slope values. Although correlation (R coeff. = -0.5) of these two variables did not indicate a significant difference ($p < .18$), a trend line created by regression analysis suggests the possibility of an inverse relationship between simulator sickness symptoms and OKCR head movements (Fig. 6).

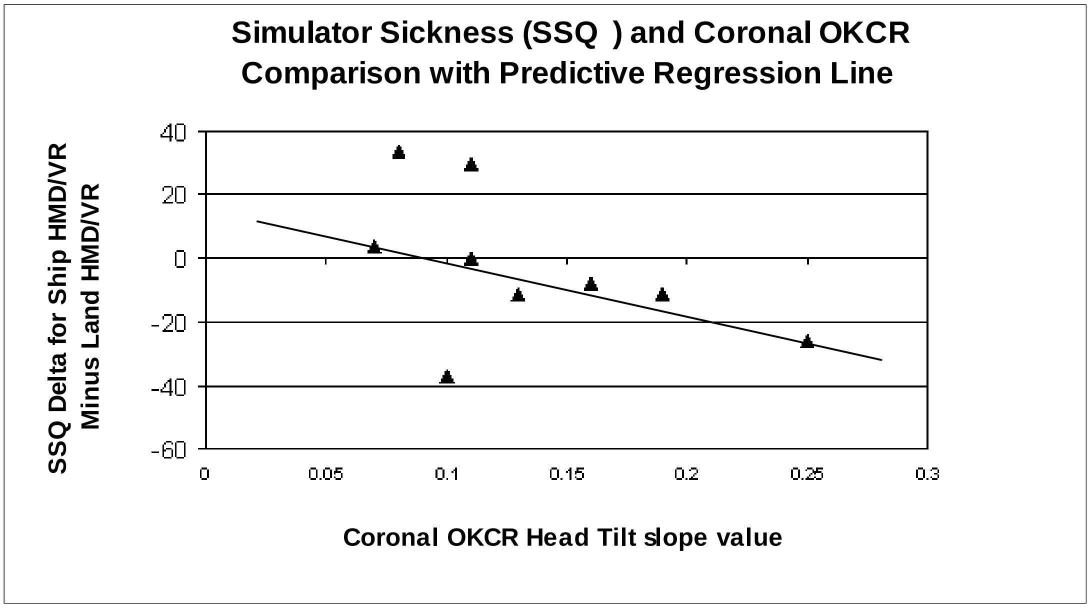

Figure 6: Correlation comparison of post HMD/VR SSQ differences (ship minus land) and coronal OKCR head tilt.

DISCUSSION

For both land and sea conditions, observed changes in coronal head position (relative to the simulated HMD/VR horizon) were consistent with OKCR responses reported in previous studies (11). Typically, pilots flying in real world environments with an unrestricted outside view (approx. 180º horizontal x 135º vertical) exhibit coronal OKCR head movements with steeper than -0.31 slope values (12); however, when FOV becomes reduced (which is typically the case with most HMDs) the horizon retinal image size shrinks and thereby attenuates the OKCR response. HMD/VR systems with relatively large FOVs (100º horizontal x 100º vertical) have been shown to cause only a slight reduction in coronal OKCR (-0.25 ± .14 slope values;13), while smaller sized systems (48º horizontal x 32º vertical FOV) were graphically illustrated by Gallimore et al., as producing a greater than 50% reduction (-0.12 slope value;14). Since the FOV used with the current study's land and sea HMD/VR trials was only slightly less (34º horizontal x 25º vertical) than that used by Gallimore et al., is was not surprising to find similar coronal OKCR slope values of -0.14 ± .06 for land and -0.13 ± .06 for shipboard observations.

When sagittal OKCR head pitch was compared with aircraft bank angles, values for both land and sea HMD/VR conditions (maximums of 10.1º for land and 11.6º at sea) were similar to observations reported with past experiments. Gallimore et al., documented that flight simulations with a circular 40º FOV triggered sagittal (OKCR) head pitch variations that reached a maximum of eight degrees and also noted that reducing FOV significantly increased the variance of this response (13). Since reductions in HMD vertical FOV places limits on the effectiveness of up-and-down eye motions, the

observed increase in sagittal head variance might be attributable to compensatory head movements that in this circumstance, and would help to expand and restore the vertical field of regard.

Unlike the observed OKCR head responses for coronal and sagittal planes, OKCR head yaw appeared to increase significantly (p = .04) during the shipboard HMD/VR trials. Post hoc analysis of left and right head yaw indicated movement toward the right was significantly greater during HMD/VR simulations performed aboard ship; however, left head yaw did not differ significantly between the land and ship conditions. Since the ship's clockwise octagonal course required a total of 15 right turns (each turn lasted approximately 24 seconds), the subsequent centrifugal and left roll accelerations may have stimulated the subjects' vestibular and proprioceptor systems in a manner that biased head yaw movement toward the right. If this were the case, it raises the possibility that vehicle movement unsynchronized with visual spatial information may confound spatial perception by invoking postural changes that oppose retinal spatial cues. This circumstance could be accurately described as a condition of sensory conflict, which in addition to confounding spatial perception, is known to be a causative factor of motion sickness.

Although Muth and Lawson reported a negligible increase in simulator sickness during shipboard usage of a fixed three monitor flight simulator, the HMD/VR system used for the current study induced significant cybersickness for both ship and land based flight conditions. During the blindfolded shipboard trials, SSQ scores were only slightly above baseline; however, SSQ averages for land and sea HMD/VR simulations were more than four times greater than those observed during the shipboard blindfolded condition and nearly five times greater than pre-trial baseline scores. Since morbidity rates for cybersickness are known to be high with HMD/VR systems, it was not surprising to find that subjects reported increased discomfort ranging from mild to severe for both land and sea trials.

A post hoc evaluation of the subjects' cybersickness reaction was made by correlating SSQ scores with coronal OKCR head movements. Although this correlation was not statistically significant (p = .18), it did suggest the possibility that during shipboard HMD/VR flight simulations, subjects may react to early cybersickness symptoms by limiting their head movements. This theory is anecdotally supported by comments from subjects with the two highest SSQ scores: during post experiment debriefs these subjects spontaneously reported that during shipboard simulations, they intentionally limited their head movements in response to the onset of cybersickness symptoms. Since virtually all subjects reported some level of discomfort during both land and sea HMD/VR conditions, it might prove useful to further investigate the possibility of a predictive relationship existing between reflex head responses and onset of cybersickness.

Conclusions

The fact that coronal and sagittal OKCR did not differ significantly between land and sea conditions suggests low levels of incongruent ship movement do not interfere with

spatial perception of a simulated rolling horizon. However, with regard to OKCR head yaw, the data suggests incongruent motion with a directional bias (i.e. ship turn acceleration) has the potential to increase head yaw and thereby alter visual perception of shipboard fight simulations.

The findings of this study indicate spatial reflexes, such as OKCR, appear resilient enough to withstand random low level sensory noise (incongruent ship motion); however, when incongruent sensory stimulation becomes focused (i.e., centrifugal force from sustained turns), spatial reflex responses can become altered and thereby have the potential to impact cybersickness susceptibility and training effectiveness. Also confirmed by this study is the fact that shipboard use of an HMD/VR simulator will produce significant levels of cybersickness, similar to what has been previously reported with land based experiments.

Since learning how to pilot an aircraft is dependant upon formulation of accurate spatial strategies, any training environment that produces a deviation from real world reflex responses has the potential to produce a negative training experience. To enhance training benefits and minimize risk of cybersickness during shipboard HMD/VR flight simulations, future research should be aimed toward defining human adaptability to training simulations in the presence of incongruent motion.

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